Midterm Exam for Undergraduates

EES 3310 Global Climate Change

Wednesday, February 19, 2020

Answer Key

Multiple Choice Questions:

Choose the one alternative that best completes the statement or answers the question. Mark your choice on the optical scan sheet.

1. If people were not emitting any CO_2 into the atmosphere, describe the relationship between silicate weathering and volcanic ougassing of CO_2. (Don't assume that volcanic outgassing is constant.)

   (a) Silicate weathering would be constant.

   (b) Silicate weathering would vary, but it would depend on the temperature and would not be affected by outgassing.

   (c) If volcanic outgassing changed, silicate weathering would act as a positive feedback and amplify the change.

   $\boxed{\text{(d)}}$ If volcanic outgassing changed, silicate weathering would change over time to become equal to the outgassing.

   (e) If silicate weathering changed, volcanic outgassing would change to become equal to silicate weathering.

2. Molecule for molecule, methane is a much more powerful greenhouse gas than carbon dioxide. Why is this?

   (a) Because methane has a much longer lifetime in the atmosphere than carbon dioxide.

   (b) Because plants remove carbon dioxide from the atmosphere by photosynthesis, but they do not remove methane.

   $\boxed{\text{(c)}}$ Because carbon dioxide is strongly band-saturated but methane is not.

   (d) (a) and (b)

   (e) All of the above.

3. Which of the following is a flaw in layer models of the greenhouse effect?

   (a) Layer models assume that the atmosphere is completely opaque to longwave radiation, but the atmosphere is partially transparent to some longwave radiation.

   (b) Layer models assume that the emissivity of the atmosphere (ε) is the same for all wavelengths of longwave radiation, but the emissivity is actually very different for different wavelengths.

   (c) Layer models assume that radiation is the only thing that carries heat away from the surface.

   (d) (a) and (c).

   $\boxed{\text{(e)}}$ all of the above.

4. Which of the following feedbacks is negative

   (a) water vapor

   $\boxed{\text{(b)}}$ silicate weathering

   (c) ice-albedo

   (d) (b) and (c)

   (e) None of the above

5. Low clouds in the atmosphere ________ the albedo and ________ the greenhouse effect, so they ________ the surface temperature.

   (a) increase, strengthen, have little effect on.

   (b) decrease, weaken, cool.

   $\boxed{\text{(c)}}$ increase, have little effect on, cool.

   (d) have little effect on, weaken, cool

   (e) have little effect on, strengthen, warm

6. What do changes is the ratio of $^{13}C/^{12}C$ tell us about the cause of rising CO_2 levels?

   (a) The ratio of $^{13}C/^{12}C$ tells us about the age of the source of extra carbon.

   (b) The ratio of $^{13}C/^{12}C$ tells us about whether the extra carbon comes from sources on land or in the oceans.

   $\boxed{\text{(c)}}$ The ratio of $^{13}C/^{12}C$ tells us about whether the extra carbon comes from biological or mineral sources.

   (d) The ratio of $^{13}C/^{12}C$ tells us about whether the extra carbon comes from oxidized or reduced forms of carbon.

   (e) None of the above.

7. A chemist who has invented a new chemical asks you to help her determine whether it is a greenhouse gas. To figure this out, you need to measure the following:

   (a) Whether it strongly absorbs longwave radiation

   (b) Whether it strongly absorbs shortwave radiation

   (c) How long it stays in the atmosphere

   $\boxed{\text{(d)}}$ Both (a) and (b)

   (e) all of the above

8. Ignoring the effect of feedbacks, how do radiative-convective models represent the effect of adding more CO_2 to the atmosphere?

   (a) The lapse rate increases.

   (b) The lapse rate decreases.

   $\boxed{\text{(c)}}$ The skin height rises.

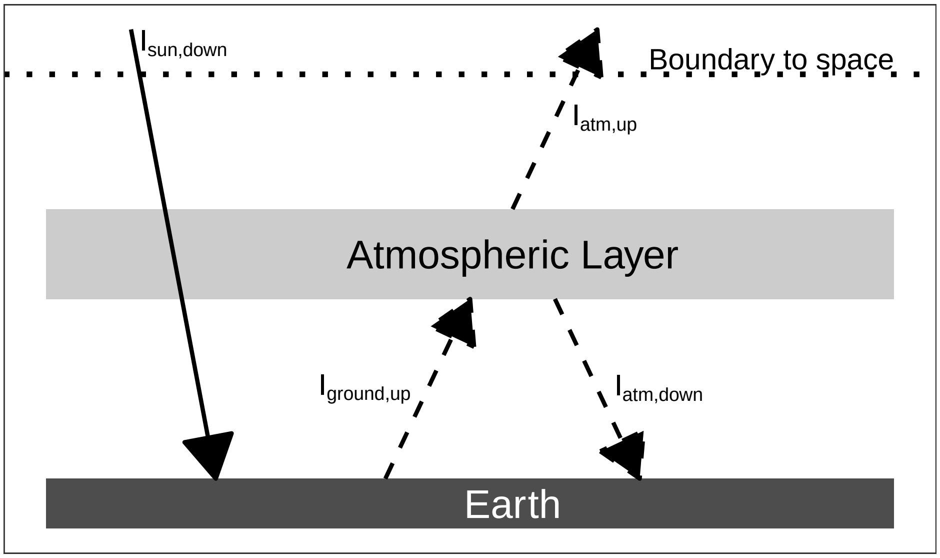
   (d) The skin height falls.

   (e) The skin height and the lapse rate both change.

Short Answer Questions:

1. Consider a layer model of the atmosphere, as shown below.

   NOTE: You do not have to do complicated calculations with the Stefan-Boltzmann equation for this problem. You should be able to answer the different parts simply, using only the quantities I shown in the diagram. You do not need to calculate numbers for the intensities.



   (a) How does $I_{\text{atm, up}}$ compare to $I_{\text{sun, down}}$? Why?

   ANSWER: $I_{atm,\ up} = I_{sun,\ down}$. *This is a simple balance of heat at the boundary to space.* ***(6 points).***

   (b) How does $I_{\text{atm, down}}$ compare to $I_{\text{atm, up}}$? Why?

   ANSWER: $I_{atm,\ down} = I_{atm,\ up}$. *The intensity is given by the Stefan-Boltzmann law* $I = \sigma T^4$ *and in a layer model the temperature of a layer is the uniform so the bottom of the layer has the same temperature as the top.* ***(6 points).***

   (c) The heat going into the ground has to balance the heat coming out ($I_{\text{ground, up}}$). Write a mathematical formula for the heat going into the ground in terms of the intensities I that appear in the diagram. You *do not need to solve the equation*, just write it down.

   ANSWER: $I_{into\ ground} = I_{sun,\ down} + I_{atm,\ down}$. *You could simplify this to* $I_{into\ ground} = 2I_{sun,\ down}$ *because* $I_{atm,\ down} = I_{sun,\ down}$*, but that's not necessary.* ***(5 points).***

   (d) If you took the atmosphere away (i.e., turned this into a bare rock model with no layers), how much would the heat going into the ground change (give a numeric ratio, such as "it would increase by 30%" or "it would be 40% smaller.").

   ANSWER: *In the bare rock model,* $I_{into\ ground} = I_{sun,\ down}$*, so the heat in reduces from* $I_{sun,\ down} + I_{atm,\ down}$ *to* $I_{sun,\ down}$*, which means it becomes 50% smaller because* $I_{atm,\ down} = I_{sun,\ down}$. ***(3 points).***

2. The thermocline in the ocean plays a very important role in controlling how the ocean responds to rising temperatures and rising levels of carbon dioxide.

   (a) What is the thermocline?

   ANSWER: *It is a layer in the ocean where the temperature changes very quickly with depth. Above it, the water is warm and below it the water is cold. It acts as a barrier that prevents the warm water above from mixing with the cold water below.* ***(4 points).***

(b) How does the thermocline affect the ocean's ability to absorb CO_2?

ANSWER: *The thermocline stops the warm water above it from mixing with the cold water below it. This prevents carbonate from the deep oceans from replenishing depleted carbonate in the mixed layer near the surface. This slows down the rate at which the ocean can absorbe CO_2.*
A different correct answer would be to say that it prevents CO_2 dissolved in the mixed layer near the surface from mixing with the deep ocean water, and thus slows down the absorption of CO_2 by the ocean. ***(4 points).***

(c) In the ocean, water at the bottom is coldest and the warmest water is at the surface. How does this compare to air temperatures in the troposphere (the lower 10 km or so of the atmosphere)?

ANSWER: *In the troposphere, the air at the bottom of the atmosphere is warmer than the air higher up. This part is all that's necessary for a correct answer.*
Students do not need to provide the detail below, but this is important because of the relationship between temperature and convection: Warm air rises, so the atmosphere tends to have convection, which mixes the air, whereas in the ocean, the warm water is already at the top so there is no convective mixing. ***(4 points).***

(d) What is the principal cause of the distinctive ways that the temperature varies with depth or altitude in the oceans and troposphere?

ANSWER: *The reason the atmosphere is warmest at the bottom (near the ground) and the ocean is warmest at the top (near the surface) is because the atmosphere is transparent to sunlight, so the sunlight is mostly absorbed by the ground, at the bottom of the atmosphere, whereas the water in the ocean absorbs sunlight, so sunlight doesn't penetrate very far below the surface (the ocean is many miles deep, but sunlight doesn't penetrate below a few hundred feet, so the deep oceans are pitch black), and the solar energy goes into heating the top part of the ocean.* ***(4 points).***

(e) What important role does the "conveyor belt" current play in the ocean's response to rising CO_2 concentrations in the atmosphere?

ANSWER: *Because the thermocline prevents the oceans from mixing very much, the conveyor belt current is almost the only thing that mixes water from the surface layer with water from the deep oceans. In terms of CO_2 the conveyor belt brings fresh carbonate from the deep oceans to the surface. This replenishes depleted carbonate and allows the surface oceans to continue absorbing CO_2 from the atmosphere.* ***(4 points).***

3. The figure below shows the spectrum of longwave radiation seen by a satellite at night when the sky is clear, together with the intensity of longwave radiation that would be emitted from ideal blackbodies at different temperatures.

(a) Consider radiation with wavenumbers of 300, 700, 900, 1200, and 1400 cycles per centimeter. For which of these wavenumbers is the skin height close to the ground and for which is it fairly high in the atmosphere?

ANSWER: *300, 700, and 1400 are high up, which you can tell because they are cold. 900 and 1200 are fairly low because they are warm.* ***(6 points).***

(b) Do greenhouse gases absorb more longwave light for the wavenumbers corresponding to high or low skin heights?

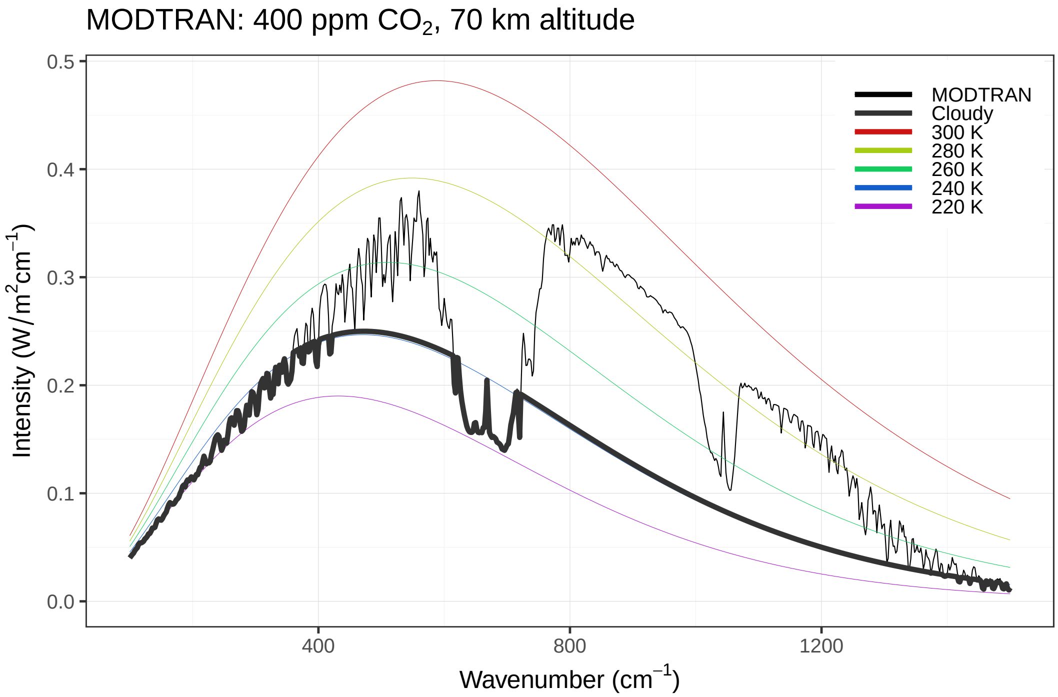
ANSWER: *Greenhouse gases absorb more light at the high skin height.* ***(6 points).***

(c) Roughly, what is the skin temperature for 700 and 900 wavenumbers?

ANSWER: *For 700, $T \approx 220\,\mathrm{K}$. For 900, $T \approx 280\,\mathrm{K}$ (a little warmer, but 280 K is close enough).* ***(6 points).***

(d) On the graph above, roughly sketch what the spectrum would look like if the sky were covered by a layer of dense clouds whose tops are in the middle of the troposphere, where the temperature is about 240 K. (**HINT:** think about skin height and how it compares to the height of the clouds.)

ANSWER: *In the window region, the clouds will behave like almost perfect black bodies, so the spectrum shoul be very close to one of the blackbody curves on the figure in that temperature range, but where the skin height is very high, such as for CO_2 the absorption features will still be visible.*
Below, I show a spectrum from MODTRAN that gives an idea what the sketch should look like, but of course the answers don't need all the fine detail that MODTRAN includes.



I don't want this to get too bogged down in details. I'm looking for something generally along the lines of a spectrum that pretty closely follows the 240 K line, except for the CO_2 peak that drops down to 220 K. ***(2 points).***

4. A scientist is studying ice cores from Antarctica and Greeenland and carbonate sediments from the deep oceans from some time a few hundred thousand years ago. She observes that at some time:

- The fraction of ^{18}O in the ice starts to rise and continues rising for around 1000 years.
- Then it levels off and remains fairly steady for several thousand years.
- The fraction of ^{18}O in the ocean sediments is fairly steady for the first 100 years or so after the fraction in the ice starts to rise.
- Then the fraction of ^{18}O in the ocean sediments gradually begins to fall, and continues falling for about 2000 years.

(a) What does the ^{18}O in the ice tell you about what happened?

ANSWER: *The air temperature warmed up for about 1000 years and then stayed warm.* ***(9 points for getting the temperature rise: 5 points for identifying temperature and 4 points for the direction of the change. Students don't need to talk about the timing.).***

(b) What does the ^{18}O in the deep-sea sediments tell you about what happened?

Answer: *The sea level didn't change much for 100 years or so and then rose for about 2000 years.* ***(9 points for getting the sea-level rise: 5 points for identifying sea level and 4 points for getting the direction of the change. They don't need to talk about timing here.).***

(c) Why does the ^{18}O change later and more slowly in the deep-sea sediments than the ice?

Answer: *The sea level rose because glaciers were melting. Glaciers melt slowly: first the temperature rises, then the glaciers gradually melt.* ***(2 points).***

Students don't need to say this to get points, but there's some interesting detail: When the temperatures start to rise, most of the glaciers are at subfreezing temperatures. The glaciers don't start to melt until the temperature rises above freezing, so during the time when the temperature is rising, but is still below freezing, the glaciers won't melt.

5. Explain the effect of silicate weathering on atmospheric carbon dioxide:

The relevant reactions are:

$$\begin{array}{rcll} CaSiO_3 + CO_2 & \rightarrow & SiO_2 + Ca^{+2} + CO_3^{\ 2-} & \text{(Weathering of silicate rock)} \\ CO_3^{\ 2-} + CO_2 + H_2O & \rightleftharpoons & 2\,HCO_3^{\ -} & \text{(Carbonate buffering of sea water)} \end{array}$$

For the following question, consider only the two reactions above and the fact that CO_2 gas can dissolve in water. You can neglect everything else about the carbon cycle.

(a) When there is no weathering, what happens to the amount of carbonate in the oceans when the amount of CO_2 in the atmosphere rises?

Answer: *The amount of carbonate drops as it reacts with CO_2 to become bicarbonate.* ***(7 points).***

(b) If you just look at silicate weathering and nothing else, how does silicate weathering affect the amount of carbonate in the oceans?

Answer: *Silicate weathering adds carbonate to the oceans.* ***(7 points).***

(c) Putting your previous two answers together, how does silicate weathering affect the amount of CO_2 in the atmosphere?

Answer: *Silicate weathering adds carbonate to the oceans, which increases the amount of CO_2 that can dissolve, which in turn removes more CO_2 from the atmosphere.* ***(6 points).***